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ABSTRACT

Control unit (33) is connected to all sensors (29, 31) and actuators (25, 27) and turning moments are applied to a boring bar (5) to counteract the bending forces generated by the radially and axially excited forces. The actuators, piezo-ceramic elements (25, 27), are spaced from the center axis of the bar and change size when receiving control voltage from the control unit, to produce the turning moments counteracting vibration.

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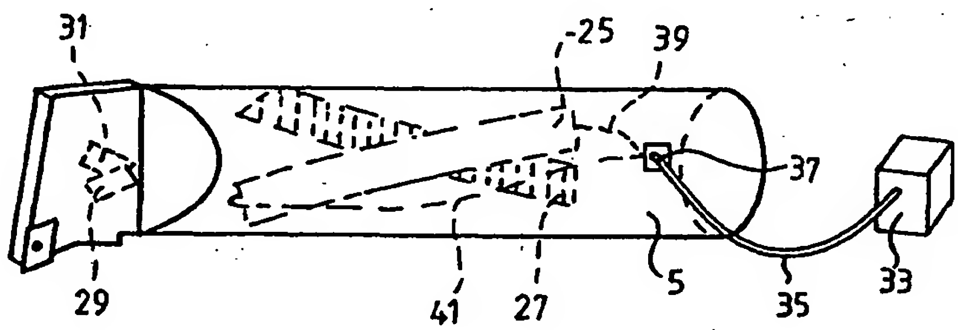

(57) Abstract

The invention relates to a device for vibration control in a machine for boring, the machine comprising a cutting tool (3) supported by a tool holder (5). The device comprises a control unit (33), a vibration sensor (29, 31) connectible to the control unit, and an actuator (25, 27) connectible to the control unit. The actuator comprises an active element (25, 27) which converts an A.C. voltage supplied by the control unit to the actuator into dimensional changes. The active element is adapted to be embedded in the body of the tool holder and is adapted to be embedded in such a manner that said dimensional changes impart turning moments to the body of the tool holder. The invention further relates to a method for vibration control in boring. The invention also relates to a tool holder (5) for boring.

METHOD AND DEVICE FOR VIBRATION CONTROL III

Field of the Invention

The present invention relates to a method and a device for vibration control, and more specifically a method and a device for vibration control in boring, and a tool holder for vibration control in boring.

Background Art

In boring, dynamic motion arises between the tool and the workpiece. The motion is largely due to the fact that the chip-forming process, i.e. the removal of the generally relatively hard material from the workpiece, results in dynamic excitation of the tool, especially the tool holder. The dynamic excitation results in a dynamic motion, in the form of, for instance, elastic bending or torsion, of the tool and the tool holder. The chip-forming process is largely stochastic and the excitation appears in the form of tool vibrations and noise. In addition to thus causing problems in the working environment, the dynamic motion also affects the evenness of the surface of the workpiece and the service life of the tool.

It is therefore important to reduce the dynamic motion as far as possible. It has been known for long that the vibration problem is closely connected with the dynamic stiffness in the construction of the machine and the material of the workpiece. It has therefore been possible to reduce the problem to some extent by designing the construction of the machine in a manner that increases the dynamic stiffness. Moreover, it has recently been possible to increase the dynamic stiffness of the tool itself and the tool holder by active methods for controlling the response of the tool. This means that active control of the tool vibrations is applied.

The active control comprises the introduction of secondary vibrations, or countervibrations, in the tool by means of a secondary source which is called actuator. The actuator is operated in such manner that the control vibrations interfere destructively with the tool vibrations.

In boring, i.e. inside turning, the tool is affected by excitation forces in the cutting speed direction, i.e. the direction of rotation of the workpiece at the cutting edge of the tool, in the direction of feed, i.e. axially seen from the perspective of the workpiece, and in the radial direction, i.e. radially seen from the perspective of the workpiece. The radial direction thus is perpendicular to the cutting speed direction. There are no known solutions for reducing tool vibrations in boring. However, attempts have been made to solve the corresponding problem in outside turning. The excitation forces in outside turning correspond approximately to the excitation forces in boring, but there are essential differences in the response of the tool holders since their design differs.

US-4,409,659 discloses an example of active control of the tool vibrations in outside turning. An ultrasonic actuator is arranged on the tool and produces countervibrations in the tool. The operating current of the actuator is controlled according to physical parameters that are measured and by means of the work of the actuator are kept within defined limits. This construction is unwieldy since the actuator is a comparatively large component which must be mounted on a suitable surface of the tool. Moreover, the directive efficiency of an ultrasonic actuator is not quite distinct.

JP-63,180,401 discloses a very different solution in outside turning, where the actuator is built into the tool holder which holds a turning insert. A laterally extending through hole which is rectangular in cross-section is formed in the tool holder. A piezoelectric

actuator, in series with a load detector, is fixed between the walls that define the hole in the longitudinal direction of the tool holder. The load detector detects the vibrations and is used by a control unit to generate, via the actuator, countervibrations which reduce the dynamic motion. This construction necessitates a considerable modification of the tool holder and indicates at the same time that the designer has not been aware of the essence of the excitation process. In fact, the modification counteracts the purpose of the construction by reducing the stiffness of the tool holder in the most important directions, above all vertically, which in itself causes a greater vibration problem, or alternatively means that the dimensions of the tool holder must be increased significantly in order to maintain the stiffness. During outside turning, the rotating tool produces a downwardly directed force on the cutting edge. When the cutting edge offers resistance, material is broken away from the workpiece. In this context, most of the vibrations arise. In JP-63,180,401, one imagines that the surface of the workpiece is uneven (wave-like) and thus mainly excites the tool holder in its longitudinal direction. Via the actuator, one generates an oscillation in opposition towards the wave pattern and thus obtains a constant cutting depth.

There is thus a need for a solution which controls the most essential vibrations, which is intended for boring (or drilling turning) and which causes a minimum of negative effects, such as bulky projections of dynamically weakening modifications, and still has a good effect.

Summary of the Invention

An object of the present invention is to provide a well-functioning method and a well-functioning device for vibration control in boring.

The object is achieved by a device and a method according to the invention as defined in claims 1 and 7, respectively.

Another object of the present invention is to provide a tool holder arranged for vibration control.

The object is achieved by a tool holder according to claim 10.

The idea of embedding according to the invention at least one active element in the tool holder implies a minimal modification of the tool holder and at the same time uses the rapidity and the capability of changing dimensions of the active element in an optimal manner. The embedding is also advantageous by the device being usable in practice since it is protected against cutting fluids and chips. In addition to the prior-art devices not being designed for boring, they are designed in a manner which possibly makes them usable for laboratories, but not in the industry.

The device according to the invention is further adapted to impart a turning moment to the tool holder through the arrangement of the active element/elements. The corresponding actuator element in JP-63,180,401 is deliberately arranged so that the dimensional change occurs along the longitudinal axis of the tool holder, which does not result in a turning moment. This depends on an incomplete idea of what primarily causes the vibration problems. Thus one has not realised that the most important excitation forces have any other direction but parallel with the longitudinal axis of the tool holder. Even with this knowledge, the construction according to JP-63,180,401, however, is not easily adjustable to any other kind of mounting than the one shown.

Brief Description of the Drawings

The invention and additional advantages thereof will now be described in more detail by way of embodiments with reference to the accompanying drawings, in which

Fig. 1 is a schematic perspective view of an arrangement of a workpiece and a tool holder with a mounted tool;

Fig. 2 is a schematic perspective view of an embodiment of the tool holder with a mounted tool according to the invention;

Fig. 3 is a schematic perspective view of another embodiment of the tool holder with a mounted tool according to the invention; and

Fig. 4 is a block diagram of an embodiment of a fedback control according to the invention.

Description of an Embodiment

In boring, a workpiece 1 is arranged in the turning lathe and is made to rotate at a certain cutting speed. Here the direction of rotation is indicated by arrow A. A turning tool 3, referred to as insert, is essentially rigidly mounted on a tool holder 5, which is referred to as boring bar. To remove material from the workpiece 1, the boring bar 5 is moved in a direction of feed indicated by arrow B. 7 designates the head of the boring bar 5, the head tapering towards the front end.

A preferred embodiment of the device according to the invention is shown in Fig. 3. It comprises a control unit 33, two actuators 25, 27 and two sensors or sensor elements 29, 31. The actuator 25, 27 comprise active elements, which here consist of piezoceramic elements. A piezoceramic element can in turn be designed as a unit or advantageously by made up as a so-called stack and/or of several partial elements. Thus, the element can be a solid body or a plurality of individual, but composed and interacting bodies. The active elements 25, 27 are characterised in that they change dimension when an electric voltage is applied across them. The dimensional change is related to the voltage. The active elements 25, 27 are embedded in, more specifically cast into, the body of the tool holder 5. The casting is carried out by forming for each active element 25, 27 a recess in the body of the

tool holder 5, whereupon the active element 25, 27 is arranged therein and covered by casting. The active element 25, 27 is glued preferably to the bottom surface of the recess. The piezoceramic elements 25, 27 are embedded fairly close to the surface of the tool holder 5, i.e. close to the circumferential surface thereof.

The sensors 29, 31 consist of piezoelectric crystals which generate an electric voltage when subjected to forces. Also the sensors 29, 31 are preferably covered by casting in the same way as the active elements 25, 27. The control unit 33 is, via a conduit 35 containing a plurality of conductors, and a terminal 37 mounted on the boring bar 5, connected to the sensors 29, 31 and the actuators 25, 27. For the sake of clarity, only those conductors 39, 41 are shown in the boring bar 5 which are connected to the one actuator 25, but of course conductors are also arranged for the other actuator 27 and for the sensors 29, 31. The conductors 39, 41 are also cast into the tool holder 5.

The mainly dynamic forces acting on the boring bar have the character of torsion. The piezoceramic elements 25, 27 are plate-shaped and elongate. By arranging them in an inclined position as shown in Fig. 3, i.e. with their longitudinal direction helically extended round the centre axis of the boring bar 5, they are essentially parallel with the resultants of the torsional forces in the body of the boring bar 5. The sensors 29, 31 are arranged correspondingly in the head 7 of the boring bar.

In an alternative embodiment as shown in Fig. 2, use is made of four active elements 9, 11, 13, 15 and four sensors 17, 19, 21, 23, which are oppositely arranged in pairs and in parallel, in the form of two pairs of sensors 17, 19 and 21, 23, respectively, and two pairs of active elements 9, 11 and 13, 15, respectively. The active elements 9, 11 of the first pair are arranged in opposing side portions of the boring bar 5. The active elements 13, 15 of the second pair are arranged in an

upper and a lower portion, respectively, of the boring bar 5. The sensors 17, 19, 21, 23 are arranged correspondingly in front of the active elements 9, 11, 13, 15 in the head 7 of the boring bar 5.

The vibration control is carried out as follows. Owing to the rotation of the workpiece 1, the chip-breaking process causes a force which, seen from the perspective of the workpiece, is tangentially directed and which acts on the insert 3. Owing to the fact that the cutting edge is spaced from the centre axis of the boring bar 5, a turning moment is generated, which shows itself as a torsional force in the boring bar 5. At the same time, the insert 3 and the boring bar 5 are exposed to forces which, seen from the perspective of the workpiece, are directed radially and axially, respectively, the axial force arising owing to the feeding in the direction of arrow B. The radially and axially directed forces cause turning moments in the form of bending. Because of the character of the chip-breaking process, said forces vary, and therefore the motions of the boring bar 5, which result from said forces, are perceived as mechanical vibrations. The vibrations occur in all directions, but the torsional vibrations are dominant.

In the embodiment in Fig. 3, the following applies. The vibrations of the boring bar 5, especially the head 7, are detected by means of the sensors 29, 31, which are subjected to alternating pulling and pressing forces. The piezoelectric sensors generate sensor signals in the form of A.C. voltages in response to the pulling and pressing forces. The control unit 23 detects the sensor signals and, in relation thereto, generates control signals in the form of control voltages, which the control unit supplies to the actuators 25, 27, more specifically to the ends of the piezoceramic elements 25, 27. The piezoceramic elements 25, 27 widen more or less in the longitudinal direction according to the frequencies and amplitudes of the control signals. The longitudinal

changes of the piezoceramic elements 25, 27 impart, through the arrangement of the piezoceramic elements 25, 27, turning moments to the boring bar 5 which generate torsional forces in the body of the boring bar 5. The power transmission to the material of the body of the boring bar 5 occurs wholly or essentially via the power-transmitting surfaces of the piezoceramic elements 25, 27. The power-transmitting surfaces consist of the end faces of the piezoceramic elements 25, 27 at the ends thereof and abut directly against surfaces in the body of the boring bar 5. The power transmission functions well thanks to the fact that the piezoceramic elements 25, 27 in this embodiment are embedded in such manner that all their boundary surfaces abut directly against the material of the body of the boring bar 5. The control unit 33 serves to generate such control voltages that the torsional vibrations introduced by the piezoceramic elements 25, 27 are in opposition to the torsional vibrations generated in the turning operation, so that the resulting torsional vibrations of the boring bar 5 are reduced.

The embodiment illustrated in Fig. 2 functions in a manner corresponding to that of the embodiment illustrated in Fig. 3. The difference between the embodiments is the arrangement of the sensors and actuators. In the embodiment in Fig. 2, in the first place vibrations in the lateral direction of the boring bar 5 up and down are counteracted. The control is carried out by the control unit 33 which is connected to all the sensors 17, 19, 21, 23 and the actuators 9, 11, 13, 15. In this embodiment, turning moments are imparted to the boring bar 5, which counteract the bending forces that are generated by the radially and axially directed excitation forces. In this as well as in the other embodiment, the piezoceramic elements 25, 27 are spaced from the centre axis I-I of the boring bar 5. The expression "spaced from the centre axis" relates generally to the fact that the centre axes

of the piezoceramic elements 25, 27 do not coincide with the centre axis of the boring bar 5. If the centre axes should coincide, no turning moment would be obtained, but merely a pure longitudinal change of the boring bar 5.

The control unit 33 is selectable among many different types, such as analog, fed-back control unit, conventional PID regulator, adaptive regulator or some other control unit suitable in a current application. Preferably the control unit strives to control the vibrations towards an optimal state. The control can imply, for example, minimising of the vibrations in one or all directions, in which case the optimal state can be completely extinguished vibrations. A large number of known control algorithms are available. It is desirable to find the most efficient one for the application.

A preferred embodiment of the control system which the control unit 33, the sensors 29, 31 and the piezoceramic elements 25, 27 constitute, is fed back and based on a so-called "Filtered-X LMS-algorithm". It is true that this algorithm is per se known to those skilled in the art. Fig. 4 illustrates an equivalent block diagram of the fed-back control system in a digital description.

Block 401, which is also designated C, represents the dynamic system controlled, which contains the actuators 25, 27 and the sensors 29, 31. The other blocks represent an implementation of said algorithm. Block 405 represents an FIR filter with adjustable coefficients, block 407 represents an adaptive coefficient adjusting means, and block 409 represents a model (C*) of the dynamic system 401.

Seen from a functional, mathematic perspective, the dynamic system constitutes a front filter, whose output signal, i.e. the response of the dynamic system, is $y_c(n)$. The coefficient adjusting means 407 strives to optimise the coefficients of the FIR filter so that an error signal $e(n)$ is minimised. The error signal $e(n)=d(n)- y_c(n)$ where $d(n)$ is a desirable output signal.

The determination of the error signal is carried out by means of a summer 411. To ensure that the coefficient adjusting means converges each time independently of its initial state, it is supplied with a reference signal r(n) from the model 409 of the front filter.

An equivalent description of the control system can be made for the embodiment in Fig. 2.

In mathematical terms it is possible to describe the effect of the invention by saying that it changes the transmission of the tool holder and, more specifically, changes the properties of one or more forward channels, each forward channel being associated with an excitation direction. This way of looking at the matter is equivalent to the effect of the invention being that control vibrations are generated, which influence the vibrations of the tool holder. It should thus be pointed out that in many cases the forward channel cannot be considered time-invariant, i.e. a traditional linear systems theory is in many cases not applicable. The system is usually non-linear.

<u>Alternative Embodiments</u>

The above specification constitutes but a non-limiting example of how the inventive device can be designed. Many modifications are feasible within the scope of the invention as defined in the appended claims. Below follow some examples of such modifications.

The above-described arrangements of the sensors and actuators are examples of arrangements and many variations are possible, such as a combination of those shown or other numbers of actuators, such as two pairs of actuators in each direction or a plurality of actuators adjacent to those shown. In its simplest embodiment, the inventive device comprises only one actuator which comprises one active element. This, however, results in a more non-linear control system, which causes unnecessary technical difficulties in controlling. Therefore it is an advantage to balance the system by arranging, like in the

embodiments shown, the active elements in pairs opposite each other, i.e. opposite each other on each side of the centre axis of the tool holder, such as the elements 9 and 11 in Fig. 2 or the elements 25 and 27 in Fig. 3. A still greater linearity is achieved if each actuator is besides formed of two active elements which are joined, for instance by gluing, with each other, large face to large face, into a double element. The double element will certainly be twice as thick as a single element, but gives a more dynamic effect, which sometimes is preferable.

Besides, the sensors can be of different types. In addition to those mentioned above, e.g. accelerometers and strain gauges are conceivable. The latter, however, are less suitable than the piezoelectric sensors from the environmental point of view.

For immediate and accurate detection of the vibrations, however, the above-described, embedded piezoelectric elements are preferable.

Also the active elements can be of different types within the scope of the invention. In the future, even thinner elements than those used today will probably be conceivable, for instance in the form of piezofilm (PZT). The currently preferred type, however, is piezoceramic elements.

The active elements are in respect of form not bound to be rectangularly parallelepipedal and plate-shaped as the elements shown, but the form may vary according to the application. The plate shape, however, is advantageous since it contributes to minimising the volume of the element. Moreover, an elongate form is a good property which also contributes to imparting to the element a small volume. It is preferred for the dimensional changes to occur in the longitudinal direction of the element.

The arrangement of the active elements in the tool holder may vary and certainly also affects the form. In addition to the above-described, preferred mounting

where the elements certainly are glued to the base of the recess but two opposite power-transmitting surfaces essentially generate the turning moments, other alternatives are possible. One alternative implies that the dimensional change is fully transferred via the glue joint, which in principle is possible with today's strongest glues. Also other variants are contained within the scope of the invention.

The active element is covered by casting, using a suitable material. As an example, plastic materials can be mentioned. Preferably, however, a cover of metal is arranged on top and on the same level as the remaining tool holder surface.

The design of the tool holder varies and may be, for example, T-shaped, the tool being arranged in one end of the crossbar of the T.

CLAIMS

1. A device for vibration control in a machine for drilling turning, said machine comprising a cutting tool (3) supported by a tool holder (5), the device comprising a control unit (33), a vibration sensor (29, 31) connectible to the control unit, and an actuator (25, 27) connectible to the control unit, and the actuator comprising an active element (25, 27) which converts an A.C. voltage supplied by the control unit to the actuator into dimensional changes, characterised in that said active element is adapted to be embedded in the body of the tool holder, and that said active element is adapted to be embedded in such manner that said dimensional changes impart turning moments to the body of the tool holder.

2. A device as claimed in claim 1, characterised in that said active element (25, 27) is adapted to be embedded with its centre axis spaced from the centre axis of the tool holder (5).

3. A device as claimed in claim 1 or 2, characterised in that said active element (25, 27) is adapted to be embedded close to the surface of the tool holder (5).

4. A device as claimed in any one of the preceding claims, characterised in that said active element (25, 27) is plate-shaped.

5. A device as claimed in any one of the preceding claims, characterised in that said actuator (25, 27) comprises a double element which consists of two active elements which are connected with each other via a large face each.

6. A device as claimed in any one of the preceding claims, characterised in that said active element (26, 27, 45, 47) is a piezoceramic element.

7. A method f r vibration c ntrol in drilling turning, comprising the steps of detecting the vibrations of a tool holder during working, and generating control vibrations in the tool holder, according to the detected vibrations and by means of at least one active element which is electrically controllable to dimensional changes, characterised by the steps of embedding said active element in the body of the tool holder and, for generating the control vibrations, imparting turning moments to the body of the tool holder by generating at least one control voltage and applying the control voltage across said active element.

8. A method as claimed in claim 7, characterised by carrying out the detection of vibrations piezoelectrically.

9. A method as claimed in claim 7 or 8, characterised by using a Filtered-X LMS-Algorithm as control algorithm for generating the control voltage.

10. A tool holder for drilling turning, the tool holder (5) comprising an actuator (25, 27), said actuator comprising an active element (25, 27) which is electrically controllable to dimensional changes, characterised in that the active element (25, 27) is embedded in the body of the tool holder and is adapted to impart, through said dimensional changes, turning moments to the body of the tool holder.

11. A tool holder as claimed in claim 10, characterised in that said active element (25, 27) is embedded with its centre axis spaced from the centre axis of the tool holder (5).

12. A tool holder as claimed in claim 10 or 11, characterised in that said active element (25, 27) is embedded close to the surface of the tool holder (5).

13. A tool holder as claimed in claim 10, 11 or 12, characterised in that at least one pair of elements is arranged in such manner that the activo ele-

ments included in the pair are oppositely arranged on each side of the centre axis of the to l holder (3, 23, 41).

14. A tool holder as claimed in any one of claims 10-13, c h a r a c t e r i s e d in that at least one active element (25, 27) is arranged helically round the centre axis of the tool holder (5).

15. A tool holder as claimed in any one of claims 10-14, c h a r a c t e r i s e d in that it comprises an embedded, piezoelectric sensor element (29, 31).

16. A tool holder as claimed in any one of claims 10-15, c h a r a c t e r i s e d in that said embedded elements (25, 27, 29, 31) are cast into the body of the tool holder (5).

17. A tool holder as claimed in any one of claims 10-16, c h a r a c t e r i s e d in that at least one actuator (25, 27) comprises two active elements which are connected with each other via a large face each to form a double element.

18. A tool holder as claimed in any one of claims 10-17, c h a r a c t e r i s e d in that said active elements (25, 27) is a piezoceramic element.

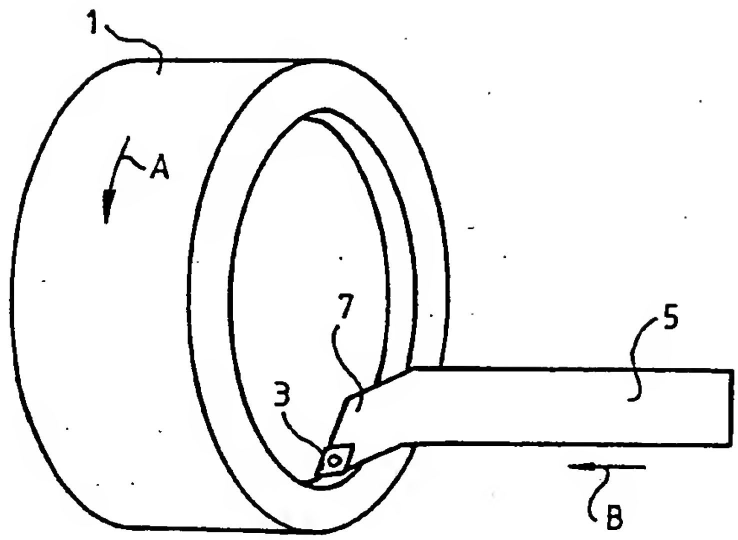

Fig. 1

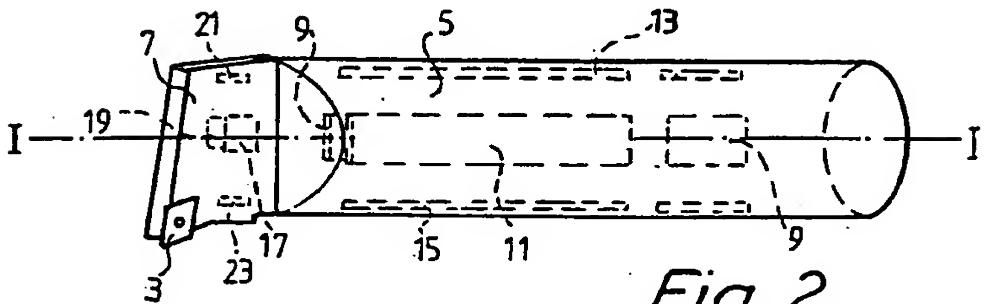

Fig. 2

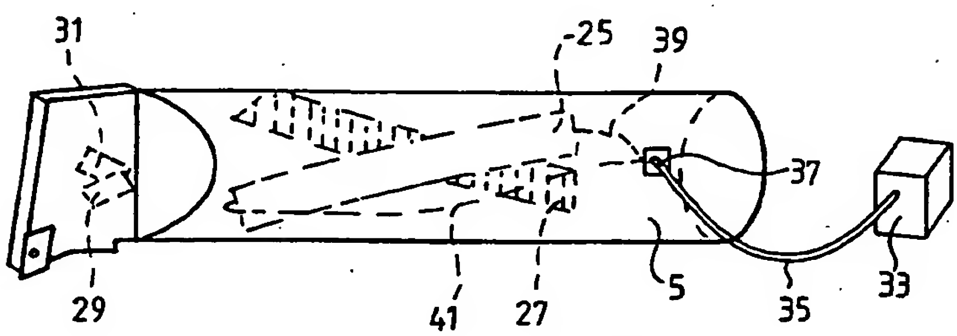

Fig. 3

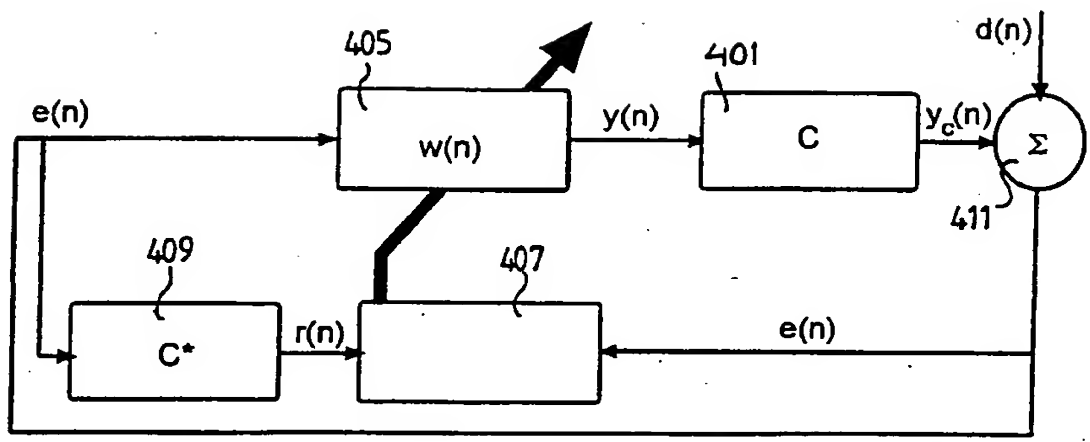

Fig.4

INTERNATIONAL SEARCH REPORT

International application No.
PCT/SE 99/01885

A. CLASSIFICATION OF SUBJECT MATTER

IPC7: B23B 29/12, F16F 15/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC7: B23B, B23C, B23Q, F16F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

SE,DK,FI,NO classes as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

WPI, EPODOC, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	Patent Abstracts of Japan, Vol 12,No 448, M-768 abstract of JP 63-180401 A (MITSUI ENG & SHIPBUILD CO LTD), 25 July 1988 (25.07.88) --	1-18
Y	US 5485053 A (BAZ), 16 January 1996 (16.01.96), column 5, line 52 - line 60, figure 32, abstract --	1-18
A	US 4849668 A (CRAWLEY ET AL), 18 July 1989 (18.07.89), figure 4, abstract --	1-18

[X] Further documents are listed in the continuation of Box C. [X] See patent family annex.

* Special categories of cited documents:

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Date of the actual completion of the international search	Date of mailing of the international search report
4 February 2000	16 February 2000 (16.02.00)
Name and mailing address of the ISA/	Authorized officer
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INTERNATIONAL SEARCH REPORT

International application No.
PCT/SE 99/01885

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 9220482 A1 (UNIVERSITY OF KENTUCKY RESEARCH FOUNDATION), 26 November 1992 (26.11.92), figures 2,7, abstract --	1-18
A	EP 0715092 A2 (AT&T CORP), 5 June 1996 (05.06.96), figures 1-2, abstract -- --------	1-18

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/SE 99/01885

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